Optimization of a fiber grating film sensor based on dual peak resonance*

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Based on the dual peak resonance of long-period fiber grating(LPFG), a novel film sensor is presented, in which films sensitive to the surrounding gases are coated on the cladding of the fiber grating region, and the intervals of the dual peak resonant wavelengths change with the film refractive index. According to the coupled-mode theory, a triple-clad numerical model is developed to analyze the relation between the sensitivity S_n and the thin film optical parameters (the film thickness h_3 and the refractive index n_3) and the fiber grating parameters (the grating period Λ and the core index modulation σ). By using optimization method, the optimal film optical parameters and the grating structure parameters are obtained. Numerical simulation shows that the sensitivity of this scheme to refractive index of the films is predicted to be more than 10^{-7}. The theoretic analysis provides straightforward foundation for the actual highly sensitive film sensors.

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Long-period fiber grating (LPFG), which was first reported in 1995[1], is a kind of fiber devices with photo-induced periodic modulation of the refractive index in the core. Because of its numerous attractive properties including ease of fabrication, low insertion loss, low-level back reflection and compactness, it is extensively used in fiber-optic communication and sensing areas, especially in chemical sensing area[2-5]. Shu X W et al. found that when grating period is short (100 μm), the dual resonant peaks of higher cladding mode appear. The dual resonant wavelengths shift in opposite direction due to the variation of the environmental refractive index, leading to a method to fabricate a high sensitivity liquid concentration sensor[6,7]. At present, an LPFG chemical sensor on which the cladding is overlaid a sensitive thin film has attracted extensive interest. Gu Z T et al. have studied the response of a LPFG gas-sensing sensor coated with the sol-gel derived films. This kind of sensor has advantages of specification of chemical analyze and broad response range, which is suitable for in-site industrial solution concentration monitoring.

In this paper, a new kind of LPFG dual resonance thin film sensor is presented. A sensitive thin film was coated on the cladding of the LPFG by sol-gel technique. The film is very sensitive to the gas environment, which is applied to monitor specific gas and enlarge sensing application range. When this kind of sensor is brought into touch with external gases, the refractive index of thin film changes. That leads to the variation of the transmission curve and the interval between dual resonant peaks.

In order to bring the variation of the interval between the resonant peaks of transmission curve into play to the utmost, the optical parameters of sensing film and the grating parameters must be optimized to improve the sensor's sensitivity. In this paper, the sensitivity of the dual resonant sensor is defined; the influence of the refractive index and thickness of thin film and the grating parameters on the dual resonant sensitivity is studied. It provides an important theoretical basis for optimizing high sensitivity LPFG thin film sensor.

Fig.1(a) shows the structural diagram of the triple-clad single mode LPFG sensor. The thin film is the chemical sensing layer. The refractive index profile of the triple-clad LPFG sensor is shown in Fig.1(b). The refractive indices of the core, cladding, sensing film and surrounding (gas) are n_1, n_2, n_3, n_4, respectively. α_1, α_2 and α_3 are the radii of the core, cladding and film. The value of (α_3- α_2) equals the film thickness h_3. The average modulation σ is the order of magnitude 10^{-4}. Generally, the refractive index of the thin film is larger than

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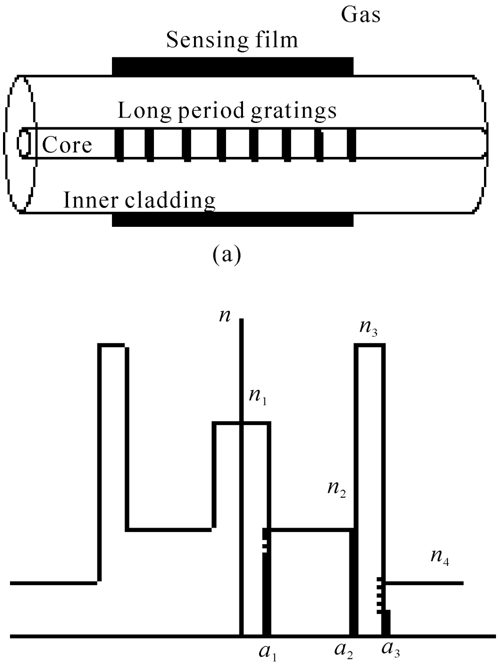
that of the core; the refractive index of the environment (gas) is about 1; the grating length is approximately a few centimeters.



(a)

(b)

Fig.1 Triple-clad long-period fiber grating gas-sensitive film sensor model (a) structural diagram; (b) refractive index profile

For single mode LPFG, the coupling between the fundamental mode propagating in the fiber and co-propagating cladding modes must satisfy the phase-matching condition

$$n_{\text{eff,co}}(\lambda) - n^{v}_{\text{eff,cl}}(\lambda) = \frac{\lambda}{\Lambda}, \quad v = 1,2,3,\cdots \tag{1}$$

where $n_{\text{eff,co}}$ (λ) is the effective refractive index for the fundamental core mode which could be obtained by solving the core mode eigenvalue equation[10]; $n^{v}_{\text{eff,co}}$ (λ) is the effective index for the v th cladding mode which could be obtained by solving the cladding mode eigen equation[11]. The effective refractive index of the fundamental core mode and the cladding mode is a function of the wavelength. The wavelength λ that satisfies the equation (1) is called as the resonant central wavelength of azimuthal order l=1 and v angle number, or resonant wavelength simply.

The resonant wavelengths change with the order of the cladding mode. The higher is the order of the cladding mode, the smaller is the grating period. When the order of the cladding mode is higher, dual resonant phenomenon appears and two resonant wavelengths satisfy the equation (1).

To determine the dual resonant wavelengths, an equation is defined as follows:

$$\Delta n_{\text{eff}} = n_{\text{eff,co}}(\lambda) - n^{v}_{\text{eff,cl}}(\lambda) - \frac{\lambda}{\Lambda} \tag{2}$$

So the specific wavelength of the different cladding modes that satisfy the curve Δn_{eff} =0 are the resonant wavelength. Fig.2 shows a plot of Δn_{eff} as a function of light wavelength for the higher-order cladding modes when grating period is 206 μm. From Fig.2, we can find that when the cladding mode is 17 or 18, the dual resonant phenomenon appears, and the accordingly resonant wavelengths are obtained.

When the LPFG sensor coated sensing thin film is brought to touch with the external liquor or gas, the refractive index of the thin film changes slightly, which leads to the variation of transmission. To monitor the variation of the interval between the dual resonant wavelengths of the higher order cladding modes, the analyze and its concentration can be measured. Opto-chemical sensors must not only be sensitive to the analyze, but also have much more detective sensitivity. The former depends on the material, while the latter depends on the structural parameters of the sensor.To get high sensitivity, the thin film parameters and the grating parameters of this LPFG sensor must be optimized.

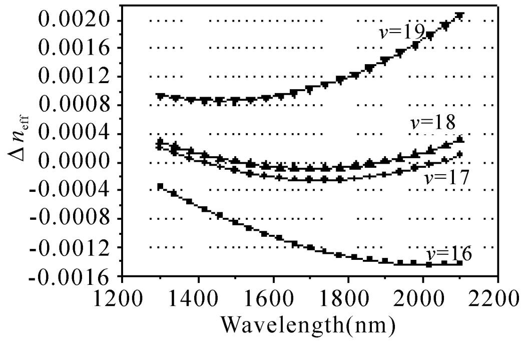


Fig.2 Plot of Δn_{eff} as a function of light wavelength (n_3=1.57, h_3=200 nm, σ=4×10^{-4}, L=1 cm)

The sensitivity of LPFG, which indicates the shifting degree of the interval between dual resonant wavelengths changing with the refractive index of thin film, is expressed as follows:

$$S_n = \frac{(\lambda_2' - \lambda_1') - (\lambda_2 - \lambda_1)}{\lambda_2 - \lambda_1} \Bigg/ \frac{\Delta n_3}{n_3} \tag{3}$$

where λ_2-λ_1 and $\lambda_2^{'} - \lambda_1^{'}$ are the intervals between the dual resonant wavelengths before and after interacting between sensor and analyze. S_n is a ratio of the change rate of the interval between dual resonant wavelengths to the change rate of the refractive index of the thin film. S_n shows the detective sensitivity because the change rate of the refractive index of the thin film directly relates to the analyze and its concentration. Obviously, S_n is function of the refractive index and the thickness of the thin film, grating parameters (period, length and average modulation), and the incident wavelength λ. By analyzing the response of the sensitivity to these parameters, the optimum film parameters and grating parameters are obtained.

Considering the convenience and practical application, two cases are discussed for sensor optimization design. One is that the refractive index n_3 and the film thickness h_3 are optimized when the grating period Λ and the average modulation σ are given, the other is that the grating period Λ, the average modulation σ and the film thickness h_3 are optimized when the film refractive index n_3 is given.

Fig.3 shows that the sensitivity S_n of the coated LPFG changes with the refractive index n_3(100-300 nm) and the film thickness h_3(1.7-1.9) when the grating structural parameters (σ=4×10^{-4}, L=1 cm, Λ=206 μm) are given. From Fig.3, a conclusion is drawn that the sensitivity S_n is different form different combination n_3 and h_3, and the value is the order of magnitude 10^2 in some range. According to the definition of the sensitivity, it indicates that when the change of refractive index of the thin film is 10^{-7}, and the spectrometer resolution is 0.01 nm, the interval variation between the dual resonant wavelengths can be observed. S_n in the blank area of Fig.3 is 0, which shows that the dual resonant wavelengths can not appear for the combination n_3 and h_3 as grating parameters given. So the parameters in the blank area should be rejected to design the sensors.

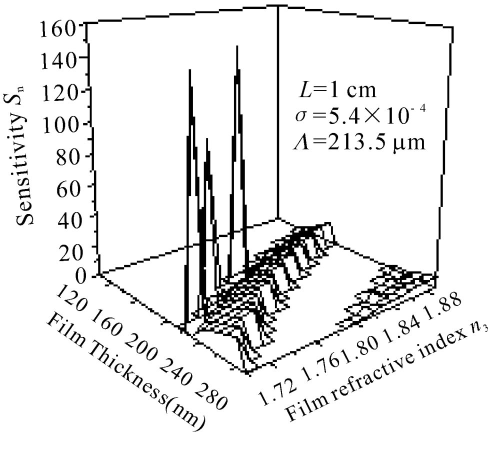


Fig.3 Dependence of $S_n|_{max}$ on refractive index for h_3 ranging from 100~300 nm

The dual resonant wavelengths are influenced by the grating structural parameters of LPFG. It directly influences the sensitivity S_n. Fig.4 shows the relations between the sensitivity S_n and the grating period and the thickness of thin film when the refractive index of thin film is given. The result indicates that high sensitivity can be achieved by adjusting grating period and overlaying proper film thickness. Compared with Fig.3, the ranges adjusted to get high sensitivity are much broader. Fig.5 shows that the sensitivity S_n changes with the grating period and the average modulation. High sensitivity can be obtained by adjusting average modulation by the exposure time and film thickness by coating technology.

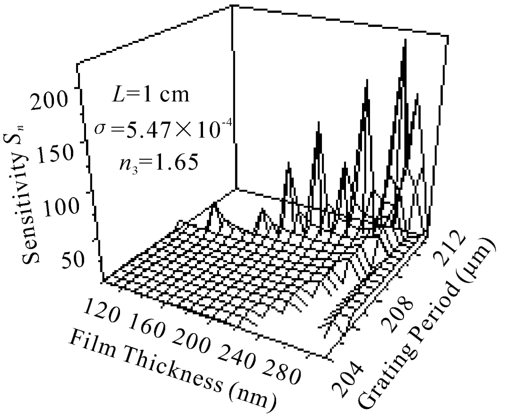


Fig.4 Dependence of $S_n|_{max}$ on grating period for h_3 ranging from 100~300 nm.

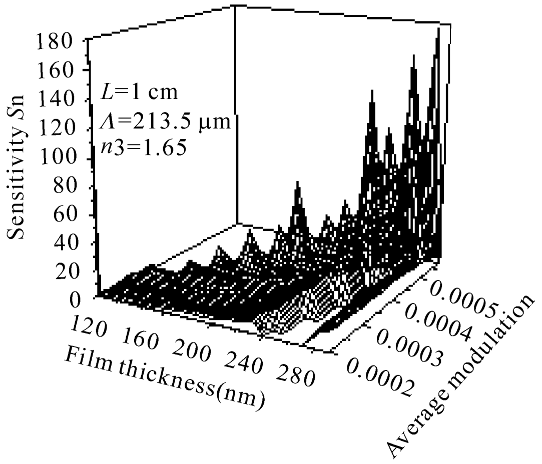


Fig.5 Dependence of $S_n|_{max}$ on refractive index modulation for h_3 ranging from 100~300 nm.

A new kind of LPFG thin film sensor is designed by overlying a sensitive thin film on the cladding of LPFG. The new LPFG would induce the dual resonant peaks, and the interval between dual resonant peaks change with the refractive index of thin film.

Different thin film parameters and grating parameters influence the interval between dual resonant peaks, so proper parameters must be chosen to satisfy the high sensitivity. By means of analyzing the theory and characteristics of the dual resonant peaks, the sensitivity of sensor is defined; the relations between the sensitivity and parameters of thin film and grating are analyzed; and the parameters used to design the sensor are given. The theoretical results indicate the resolution of this kind of sensor to the refractive index of thin film is high to 10^{-7}.

Compared with dual-cladding LPFG, trip-cladding LPFG hes much higher refractive index sensitivity. This new kind of sensor monitorsis not only the concentration of gases but also the refractive index and concentration of liquids. This sensor will be applied in the chemical, biological and environmental detecting areas and so on, extensively.

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